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New Lifing Methodology for Engine Fracture Critical Parts

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1 INTRODUCTION

Within gas turbine aeroengines, fracture critical parts are defined as those whose failure would hazard the entire aircraft. Consequently, it is of central importance to the airworthiness of these engines that the probability of such a component suffering an in-service failure is kept below acceptable levels. In order to achieve this, lifing methodologies have been devised which provide a means for calculating the required limits. These methodologies consist of a material test requirement, together with a calculation process based on a statistical characterisation of the material/component behaviour. The outstanding safety record achieved by commercial and military aeroengines is in large part due to the success of these lifing methods.

Over the last 30 years or more, considerable research activity has been devoted to developing these methodologies, and the models and assumptions that underlie them. This has ensured that the methods have kept pace with the developments in gas turbine technology, and provide safe lives which fully reflect the characteristics of the relevant components. However, the commercial pressure on engine manufacturers to produce engines with improved performance and reliability at lower cost is at least as great today as at any previous time. Consequently, the rate of development of the technologies on which engine design and manufacture is based is, if anything, increasing. The introduction of new techniques in materials development and processing, component manufacture and design analysis is ongoing and rapid. In view of these developments, the lifing methods themselves must constantly be re-evaluated and updated if the safety record achieved to date is to be maintained and improved.

Recently, the trends in aero gas turbine design have raised questions with regard to the applicability of the lifing methods used previously within the UK. The fact that engine temperatures and speeds continue to rise has meant that the components, and the materials from which they are manufactured, have been operating closer to the limit of their capability than ever before. One result of this has been that certain parameters, previously seen to have little effect on the fatigue life, are now observed to play a significant role. Moreover, the interactions between these parameters are observed to be increasingly important, and must be characterised an understood if accuracy is to be ensured. Furthermore, since these effects are also observed to have differing characteristics during the initiation and propagation phases of fatigue life, it is becoming increasingly important to distinguish between the two. All of these effects mean that significant developments in lifing methodology are required if the required accuracy of estimation is to be ensured.

In this paper, a new lifing methodology is described, which combines several features of lifing analysis in a novel way. The main elements of this methodology are, firstly, a 3-D non-linear finite element stress analysis, which is used to estimate the actual stresses experienced in service by the component. Secondly, both the crack initiation and propagation phases of life consumption are modelled explicitly, so that the most appropriate behaviour models can be used throughout the fatigue process. Finally, it explicitly includes a statistical model for the size effect in fatigue, so that any component feature can be assessed from plain specimen data alone. The methodology has been extensively validated against a database of fatigue results for a typical engine alloy, and has been demonstrated to provide accurate estimates of specimen and component life under extreme combinations of both stress and volume.

Paper presented at the RTO AVT Symposium on "Ageing Mechanisms and Control: Part B – Monitoring and Management of Gas Turbine Fleets for Extended Life and Reduced Costs", held in Manchester, UK, 8-11 October 2001, and published in RTO-MP-079(I).

2 THE HISTORICAL DEVELOPMENT OF LIFING METHODOLOGIES

In order to appreciate clearly the requirement for improved lifing methods, and the problems that they are attempting to tackle, it is important to understand the evolution of the currently available philosophies. This allows the issues currently facing the lifing community to be seen in context, and allows the new methodology to be understood as a response to the issues that stimulated its development. Consequently, this section is devoted to a description of this development.

In the very early days of gas turbine development, fracture critical parts lifing was a relatively unimportant issue. This was because the performance of the hot end parts was so poor, and engine strips so frequent, that discs were very rarely subjected to sufficient exposure for fatigue to be a problem. Moreover, any problems that did arise were picked up by inspection. Consequently, there was little or no need to formally declare lives for these components. However, as the hot part technology began to develop, and reliability began to improve, so disc failure began to be appreciated as an issue requiring closer attention. Put simply, failures of the components began to occur in-service, and there was clearly a need to address the matter in an alternative fashion.

The response to this issue was the development of what is known today as the 'safe life' approach to engine component lifing. The basis of this method was the estimation of component life through the construction and use of empirical stress-life (S-N) curves, for the relevant materials. In order to account for the different features on an engine disc, for example, it was necessary to obtain these curves at different temperatures and for a variety of stress concentrations. Safety was built into the process by basing the design and lifing calculations not on the curves themselves, but on some curve lying below the mean line which represented a suitable statistical safety factor. In the UK, such methods were always supplemented by full scale component rig tests, which were used as the basis of service life release. However, whilst these methods generally worked well, the development of materials with superior high temperature properties, better design methods and the introduction of novel manufacturing techniques pushed back the limits of what components were expected to endure in service. As a result, it became increasingly apparent that several additional factors such as mean stress and surface finish also play an important role in determining component life. Unfortunately, the empirical nature of the traditional safe life approach meant that additional design curves had to be generated to account for these different factors. The ever-increasing amount of experimental data required to sustain this approach eventually led to the search for alternative methods.

The success of stress intensity factor based fracture mechanics in combining the effects of these different factors into a unified physical model, appeared to offer a solution to the difficulties experienced in the safe life method. Different attempts were made to utilise this theory for calculating engine component lives, each of which revolves around the establishment of an initial flaw size from which the crack growth process proceeds. One of these is the 'damage tolerance' approach, whereby the initial crack size is established on the basis of the minimum detectable by non-destructive inspection methods. Another is the 'databank' method, which back calculates from known test data to establish an effective initial flaw size, this being the initial flaw that would have caused failure in the observed time under linear elastic fracture mechanics. From a set of test results, a distribution of flaw sizes is developed, and a maximum is established on the basis of a statistical analysis. Fracture mechanics is then used again to grow the flaw to failure, this being taken as the minimum life achievable. Much research work has been devoted to developing these methods, and they have been approved for use by regulatory authorities on both sides of the Atlantic. However, the ongoing developments in gas turbine technology have once again led to a situation in which the ability of the existing methods to account adequately for all relevant effects has been questioned. In particular, disc materials are now being subjected to operating temperatures at which creep plays a significant role both in determining stabilised component stresses and as a potential failure mechanism. The improvement in fatigue resistance achieved in new materials is also usually through a longer initiation period, crack growth rates being similar or even slightly worse. In short, it is now recognised that there are inherent difficulties in deriving engine component lives from a purely linear elastic fracture mechanics based approach.

3 THE NEW LIFING METHODOLOGY

The lifing methodology described in this paper attempts to overcome the shortcomings of the philosophies previously used in the UK, in order to meet the challenges presented by modern gas turbine design. It seeks to do this by directly addressing the problems with the existing methods, and by drawing on the latest developments in the technologies underlying lifing calculations. There are three basic features which combine to create the new method, and which differentiate it from those it seeks to supersede.

The first feature of the philosophy behind this approach is that the stressing carried out for each component attempts to calculate the full stress field actually experienced in service. This contrasts to, say, the data bank method, whereby the results of the elastic analysis are known to be a simplified representation of the actual stresses. The possibility of calculating actual component stresses has only been made possible by the rapid development, in recent years, both of improved numerical analysis techniques and of the hardware on which the algorithms are run. The result of this is that non-linear 3-D stress analysis of complex component shapes can now be used as a general purpose tool. Moreover, such stress analysis techniques must include the calculation of time dependent behaviour, for the reasons discussed above. Thus, in component assessment, both plastic and creep stresses must be calculated, so that an important part of introducing of the methodology has been the development of suitable methods for doing this.

The second feature of this approach, is that the crack initiation and crack propagation phases of component life consumption are modelled separately. This is in direct response to the difficulties with purely initiation or purely propagation based models discussed above. The way that this is achieved within the framework of the method is that firstly, an engineering model for total life is fitted to the available data. Then, a model for the propagation phase is used to estimate the proportion of the total life due to this phase, and a model for crack initiation is obtained by subtracting one from the other. A significant advantage of this approach is that factors which predominantly influence initiation can be included in an appropriate way, and can be treated completely separately from those which primarily influence propagation. It also means that recent developments in materials modelling can be utilised and integrated in a straightforward manner.

The third feature of the methodology is the inclusion of a model for the size effect in fatigue. This is included as the final link which allows laboratory specimen data, generated to aid and validate materials modelling, to be included in the assessment of component behaviour. It is also in recognition of the fact that materials model development relies almost exclusively on specimen data. Whilst these specimens are designed to reflect the service loadings as closely as possible, they are typically a fraction of the size of full scale components. It has long been recognised that material volume itself plays a very significant role in determining fatigue life, and hence that specimen tests alone cannot fully describe component behaviour. Moreover, this effect is not restricted to the mean behaviour of the material; rather, the distribution of fatigue lives as a whole is dependant on volume. Thus, a further modelling step is required, which allows for the so-called size effect to be incorporated into the overall life prediction scheme.

In the subsections that follow, each of these three major features is discussed in some detail.

3.1 Stress analysis

A fundemantal concept of the current approach is that the stress and strain fields causing fatigue in any particular situation are estimated as accurately as possible. To this end, a plasticity model based on the Mroz multilayer kinematic hardening rule (ref 1) has been developed. This model extends the Prager linear hardening rule by the superposition of several yield surfaces of different sizes, each exhibiting linear behaviour with a different gradient.

To model the shakedown behaviour accurately, a technique has been developed whereby the material is allowed to relax over several cycles. The model shakedown is controlled as a linear function of the total plastic strain, and is stabilised according to certain preset limits. The model is combined with standard creep algorithms, assuming that the two phenomena are uncoupled.

3.2 Fatigue and crack propagation models

As described above, the new lifing methodology requires that suitable models for both the total life and the crack propagation behaviour are identified. Both must be capable of describing the phenomena relevant to the material behaviour under each regime, under the conditions experienced within the engine.

The fatigue life model chosen for the current analysis is that commonly referred to as the Walker strain parameter. The parameter itself has the form

$$\varepsilon_W = \frac{\sigma_{\max}}{E}\left(\frac{E\Delta\varepsilon}{\sigma_{\max}}\right)^m ,$$

where E is the material modulus, $\Delta\varepsilon$ denotes the strain range, and m is an empirical factor to account for the effects of mean stress (ref 2). The effect of temperature is included through the use of a temperature dependant modulus.

The fracture mechanics model utilised within the study uses the elementary equations of LEFM, implemented using the finite element derived geometry and stress correction factors described in (ref 3)). The particular stress intensity solutions describe the growth of surface and corner cracks in rectangular blocks, with the advantage that user defined stress fields can be applied. This is particularly important in studying the growth of cracks in notches and around other stress concentration features. However, in view of the fact that the plain specimens tests analysed within the validation exercise were conducted on circular specimens, it was decided that more appropriate stress intensity solutions were readily available and should be used. For this purpose, the handbook solutions for elliptical surface cracks in round bars under tension were chosen as being more suitable (ref 4).

In addition to these models, it is necessary to account for the fact that, under certain conditions, mechanisms other than fatigue can be the primary cause of specimen and component failure. In particular, for specimen test designed to reproduce material behaviour relating to fracture critical components, it is necessary to account for the fact that some of the failures may be due to creep rupture. For this purpose, the Rolls-Royce internal creep rupture law was used, and all specimen tests were checked for this type of failure mode before being included in the database of results.

3.3 Size effect model

Existing models for the size effect in fatigue are almost invariably based on the so-called 'weak link' hypothesis, which assumes that bulk material failure will be triggered by the failure of the weakest sub-element within the material. This is related to general material behaviour by first developing a description of the material behaviour under constant load. For non-uniform loads and arbitrary geometries, the material is broken down into much smaller volumetric units, (the size of which will depend on the stress gradients involved), and the uniform stress behaviour is applied to these small volumes. The probability distribution for bulk failure is then derived by integrating individual probability distributions associated with the volume units over the body. The resulting expression is generally quoted in the form

$$F_\Sigma(\sigma;V) = 1 - \exp\left(-\frac{1}{V_0}\int_V \left(\frac{\sigma}{\eta(x)}\right)^\beta dx\right),$$

where V_0 is the reference volume at which the parameters η and β are defined (ref 5). The expression is essentially a Weibull distribution, with the appropriately normalised integral included inside the exponential. The expression as it stands applies to fatigue strength rather than life. However, it can be applied to the latter case by simply inverting the S-N relationship appropriate to the material or situation, and using this to express the characteristic life η as a function of stress (or Walker strain).

Examination of the test data made available for the validation, however, revealed that this relationship would not be sufficient for the model. In particular, there appeared to be a linear threshold, below which no failure were observed to occur. For this reason, an expression of the form

$$F_{\Sigma}(N;V,\varepsilon_W(x)) = 1 - \exp\left(-\frac{1}{V_0}\int_V \left(\frac{N - N_0(\varepsilon_W(x))}{N_\eta(\varepsilon_W(x))}\right)^{\beta} dx\right)$$

was selected as the basis of the model. This is equivalent to the choice of a 3-parameter Weibull model to describe the failure distribution at the volume element level.

Given a suitable database of test results, the manner in which the different elements of this framework are combined to produce life estimates is illustrated in Figure 1. The database of test results should contain enough plain specimen tests to represent the behaviour of the material under all conditions of interest, and should ideally include a variety of other test results for validation purposes. The calculation procedure itself involves four main stages. In the first stage, the non-linear stress analysis is used to calculate estimates of both the plastic and creep strain accumulated for each of the tests considered. The second stage involves analysing the plain specimen data,. A creep rupture analysis is performed, to determine whether the observed failures are attributable to creep or fatigue, and those which are creep induced are then eliminated from the analysis. A statistical model is then fitted to the remaining data, to provide a description of total life. Finally, a crack propagation analysis is performed, which is then subtracted from the original test result in a suitable manner, to give the required initiation model. In the third stage, the size effect model is employed to calculate an initiation life for the particular test piece under investigation. This is achieved by substituting the expression for the position dependent stress field, together with the model for initiation life, into the size effect equation and integrating. In the final stage, a crack propagation analysis is performed for the new geometry/stress field, and added to the initiation life already calculated to provide the final life estimate.

4 VALIDATION OF THE MODEL

In order to test and validate the model as a means of predicting component life, it is necessary to acquire a suitable database of fatigue test results. This database must include sufficient plain specimen results to allow the behaviour of the material to be characterised under all conditions of interest, and some other form of test result against which the predictions of the model can be compared. For this purpose, part of the Rolls-Royce database on Wasplaloy was identified as an ideal vehicle for this purpose, and it was subsequently made available for this purpose by the company. The database itself consists of 2053 fatigue test lives, together with another 224 unfailed results. The 2053 finite lives consists of 1527 plain specimen results, 454 rotating bend tests, 33 notched specimen tests (Kt 1.66 and 2.29), 10 component rig tests and 29 washer specimen results. Not all of the data have been used in the study; thus far, only the notched specimen results and some of the component results have been included in the validation studies. It is anticipated that the remaining component results and the washer specimens will be included at a later date.

Once the stress analyses have been completed, and the data checked for possible non-fatigue failures (41 tests were rejected as being due to creep rupture), the next step in analysing the data is to fit the fatigue model to the plain specimen data. The data itself is shown in Figure 2. Given the linear appearance of the data overall, a linear S-N curve of the form

$$\varepsilon_W = (cN)^{-1/\alpha}$$

was selected as the basis for the model. This was inverted and substituted into the expression for the total probability of failure to give this equation in an explicit form. However, before the analysis could proceed, a further decision had to be made concerning the geometry over which the integral should be evaluated. Conventionally, the integral in the expression is regarded as a pure surface integral over the entire body, or, it is taken over the whole of the volume. In view of the surface sensitive nature of Waspaloy, it was initially decided that the integral should be evaluated over the surface, rather than through the volume. Unfortunately, this was found to give very poor results. However, rather than revert to evaluating the integral over the entire volume, which appeared to be somewhat unrealistic in physical terms, it was decided that the integral should be evaluated over a surface layer of the material. This appeared to be the option that makes sense physically, since in any crack initiation process it will be the layer of material at and just below the surface which will be actively influencing the process. This created two difficulties; one was to choose the depth to which the integral should be taken, and the other was to develop the capability to be able to extract the relevant information from the stress analysis output files. The latter problem was solved by developing some software to convert FE node numbers into geometrical locations, thereby providing the means to extract them, if desired. The former problem was solved by selecting a value of 0.4mm, initially for no reason other than this was convenient in terms of the meshes under investigation. (In fact, later studies established that the results of the model are rather insensitive to this parameter anyway, at least for the notched specimen results). The results obtained by this method were very much better, indicating that this approach is actually representing the real physical process.

Initially, a single line was fitted through the plain specimen data, to give the fit of the fatigue life failure model. Once this was done, the next step was to subtract the crack propagation results to give he initiation model. However, this raises a further question, namely at what crack depth does the change from crack initiation to propagation take place? This is clearly critical in determining the success of the model, and so it was decided to optimise the model with respect to this parameter. The answer obtained was 0.3mm, which was close to the conventional definition of an 'engineering crack' used to define the boundary between initiation and propagation in current UK lifing proceedures. It is also close to the surface depth parameter identified as the layer over which the integral is taken. This suggests that it may be possible to treat these two criteria as a single parameter, thus reducing the number of input parameters required.

The fatigue life model for the plain specimen data, together with the crack propagation predictions and the resulting initiation life model are shown in Figure 2. The predictions for the notched specimen results calculated using this model are shown in Figure 3 to Figure 9, and the prediction for three of the component test results are shown in Figure 11. It can be seen from these figures that the results for the notched specimens is very good, with the exception of the Kt 1.66 tests at 200C and the Kt 2.29 tests at 600C which are discussed below. Moreover, the predictions for the component tests are also very accurate. Taken together, these two sets of results are extremely important, since notched specimens and component bores represent opposite extremes in terms of both strain and volume of material. The results therefore represent a strong validation of the basic concepts, since the model is seen to produce accurate results across the entire scale of likely application.

5 Discussion

As can be seen, the results are either good or very good for all the temperatures and notch types shown, apart from two. These are the Kt 1.66 tests at 200C which overestimate the results, and the Kt 2.29 tests at 600C, which underestimate the results. Considering the first of these, a further look at the data in figure 2 reveals that the data at 500C and at 200C do not really lie on top of one another. Rather, the 200 data are somewhat below the rest, and offset from the mean line. This means that the current position of the mean line tends to overestimate the initiation life at this temperature, explaining why the results are in error in this way. To correct this, it is a simple task to fit a separate line to the 200C data, derive a temperature specific initiation model and recalculate the predictions using these new results. The result of this exercise are shown in Figure 10, where it can be seen that the overprediction has been removed. In fact, the calculations now tend to underpredict the lives, although the error is considerably smaller than in the previous calculations.

The fact that a separate fatigue life model is required to resolve specific prediction errors raises a significant question regarding the use of engineering parameters in predictive work of this kind. Namely, would it be preferable to fit a multiple regression model to the data at the outset, rather than trying to derive laws which describe the behaviour of materials under very general circumstances? Although an approach of this kind would introduce additional empirical parameters, limiting the use of the resulting model, accuracy of the kind needed in the current exercise would be easier to achieve. Whilst the desirability of obtaining universally applicable (or even generally applicable) material laws is very clear, if the law is not sufficiently accurate to allow appropriate validation of models against experimental results, then their value seems to diminish somewhat.

The discrepancies encountered in the Kt 2.29 results at 600C are somewhat more difficult to resolve. Initially, it was thought that the underprediction could be related to the fact that the Walker strain values for these results lie above the point at which the crack propagation line in figure 1 crosses the total life regressions line. In other words, the initiation life for these results is zero. Moreover, checks revealed that, at these very high Walker strain values, the plain specimens would fail in tension before reaching the critical crack size. Thus, the crack propagation life would be overpredicted, potentially leading to an underprediction of the initiation life. However, given that the specimens are failing in tension, the failure point of the plain specimens will depend on the UTS for the material. The difficulty is that the UTS is itself a random quantity, and so it is necessary to establish the statistical relationship between the UTS and the initiation and propagation lives before this type of effect can be included in the calculations. Work to establish the nature of the relationship between these quantities at very high strain values is continuing.

To develop the method further, several issues need to be addressed. Firstly, the stress analysis methodology developed thus far does not include the ability to incorporate residual stresses. This is particularly important in view of the finishing techniques applied to modern components, which deliberately introduced compressive surface residual stresses in an attempt to prolong the fatigue life. Secondly, the fracture mechanics methods currently employed are based on linear elastic fracture mechanics methodology, and do not necessarily capture all the features of crack growth at high temperatures which may significantly affect the life. Thirdly, the statistical relationship between crack initiation and propagation are not fully understood at present, and further work is required to develop suitable models to describe this. Finally, it is only when the methodology has been validated against a range of materials, that the ability to provide accurate predictions over the range of conditions of interest will have been fully demonstrated.

6 Conclusions

Modern aero engine fracture critical component design presents a number of challenges to the lifing methods which have been used previously to derive safe service lives. In particular, the rise in engine temperatures means that types of material behaviour not relevant to previous component designs are playing an increasingly important role. A New Lifing Methodology has been developed, which aims to overcome the limitations of lifing methodologies currently employed in the UK, with respect to these issues. The three main distinguishing features of this new methodology are, firstly, the advanced non-linear stress analysis techniques are employed to calculate the actual component stresses experienced in service, secondly, that explicit models of both crack initiation and crack propagation are employed, and finally, that a size effect model is incorporated, which explicitly accounts for the effect of volume on fatigue. These elements allow for the prediction of fatigue lives for arbitrary geometries and stress fields, based on the analysis of plain specimen data alone.

The model has been validated against an extensive database of fatigue results in a typical aeroengine disc material (Waspaloy). The model predictions display very good agreement with notched specimen results over a wide range of temperatures and loads. Significant discrepancy is observed at the very highest temperature/load combinations, and the source of this is still being investigated. However, the model is also observed to provide excellent agreement with component results. This is very important, because notched specimens and components represent opposite extremes in terms of both stress level and material volume. Thus, the fact that the model can provide accurate predictions in both these situations is a very strong validation of the basic concept and the implementation.

The authors would like to acknowledge the support of the Department of Trade and Industry and the Ministry of Defence for their sponsorship of the work involved.

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6) FIGURES

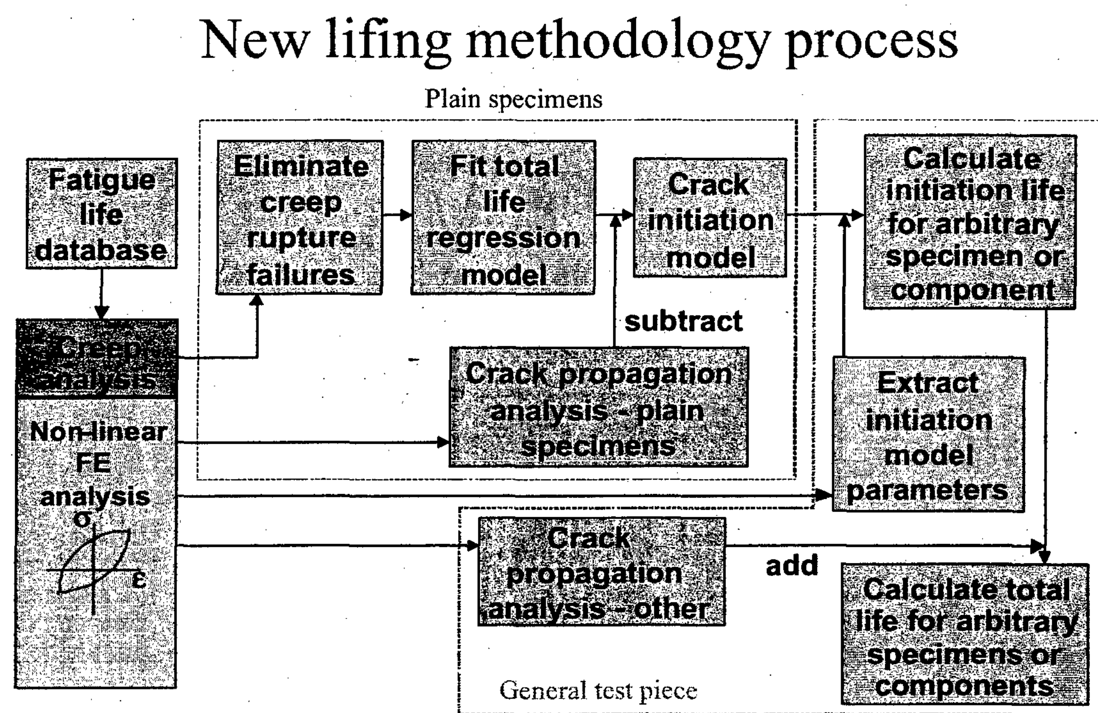

Figure 1: Framework for the new lifing methodology

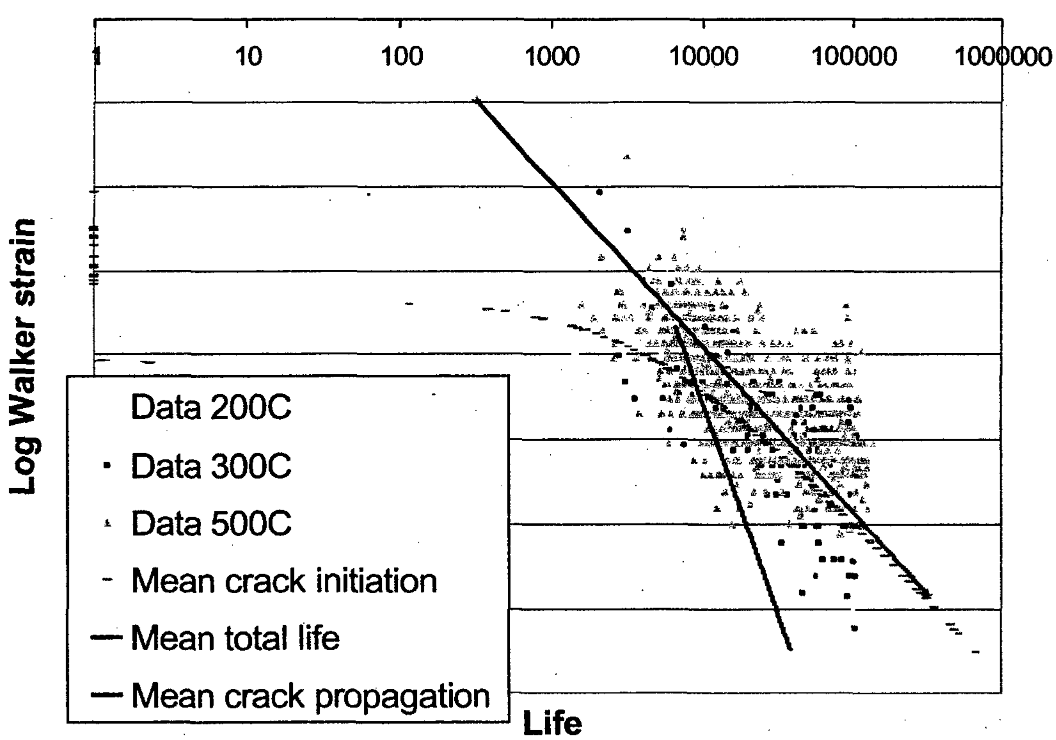

Figure 2: Derivation of the initiation model for the Waspaloy data

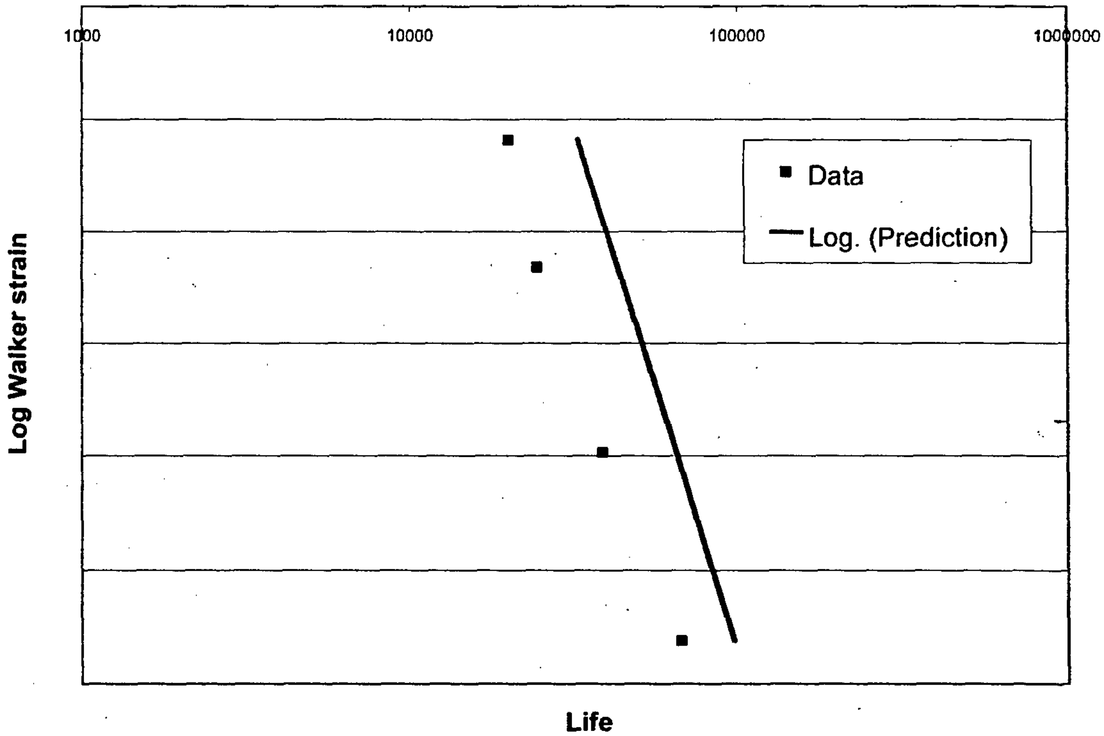

Figure 3: K_t 1.66, 200C data against prediction

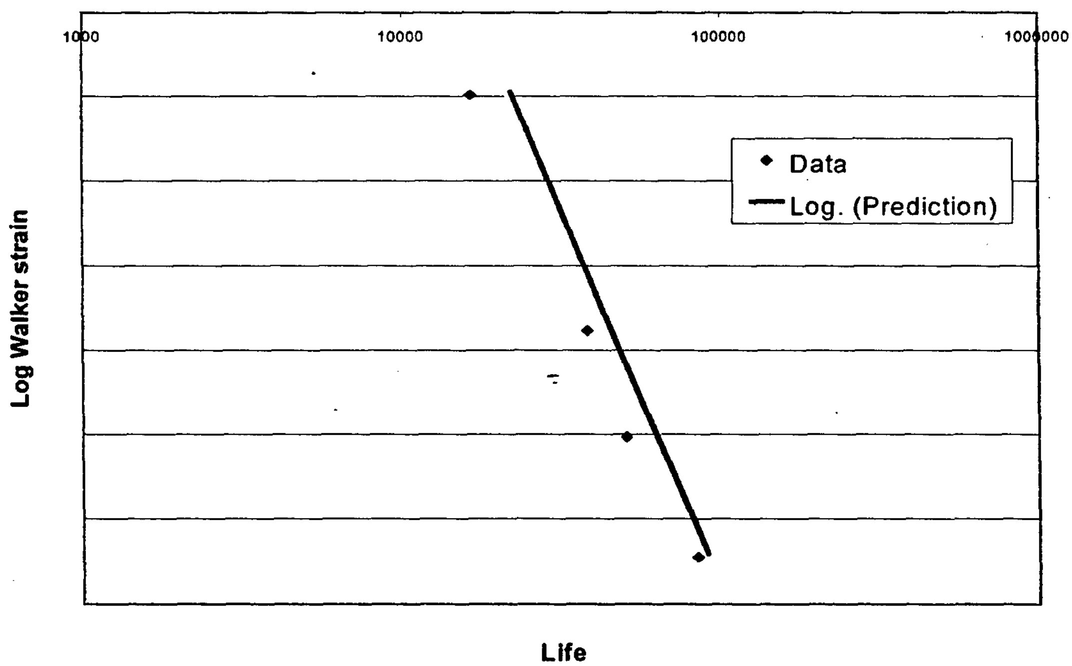

Figure 4: K_t 1.66 400C, data against prediction

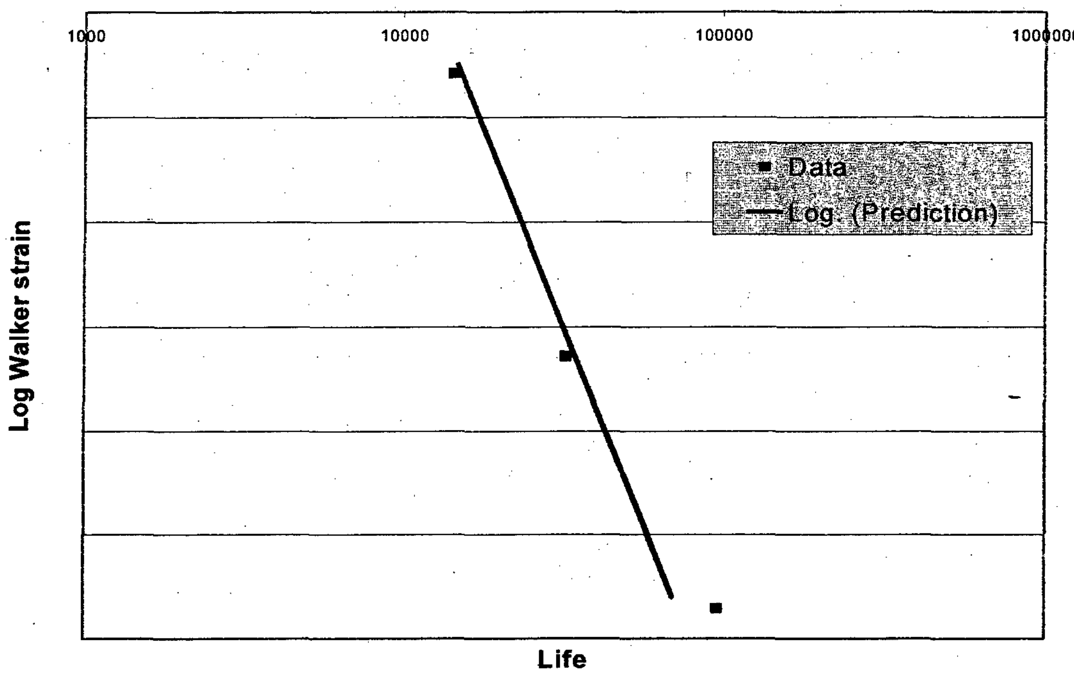

Figure 5: Kt 1.66 500C, data against prediction

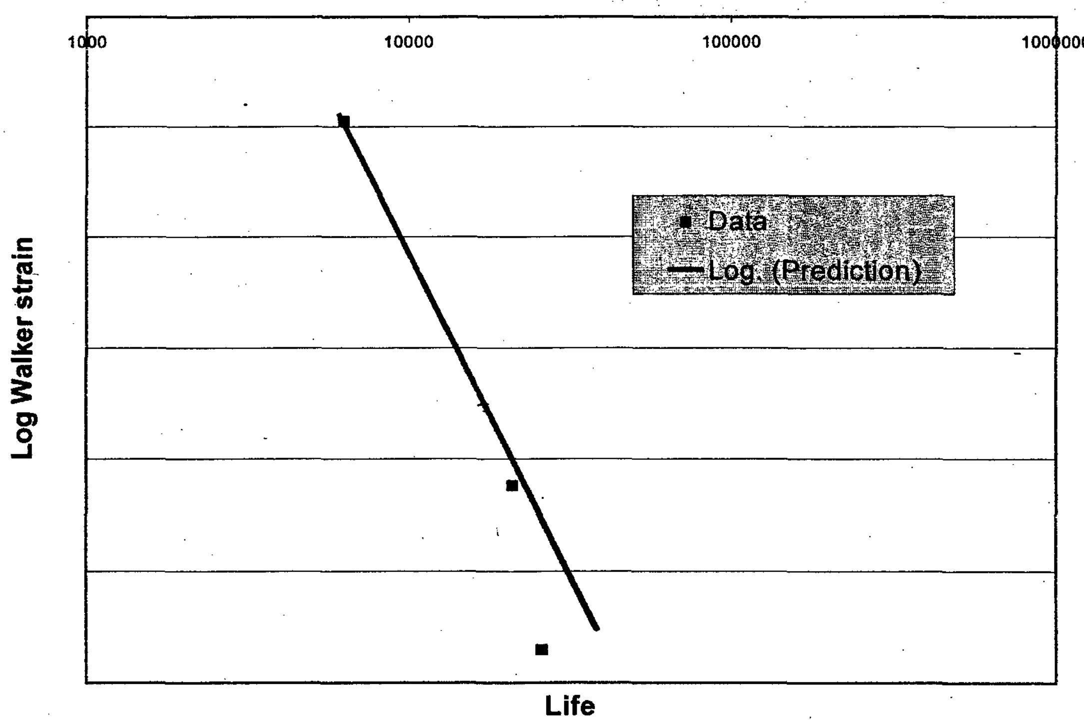

Figure 6: Kt 1.66 600C, data against prediction

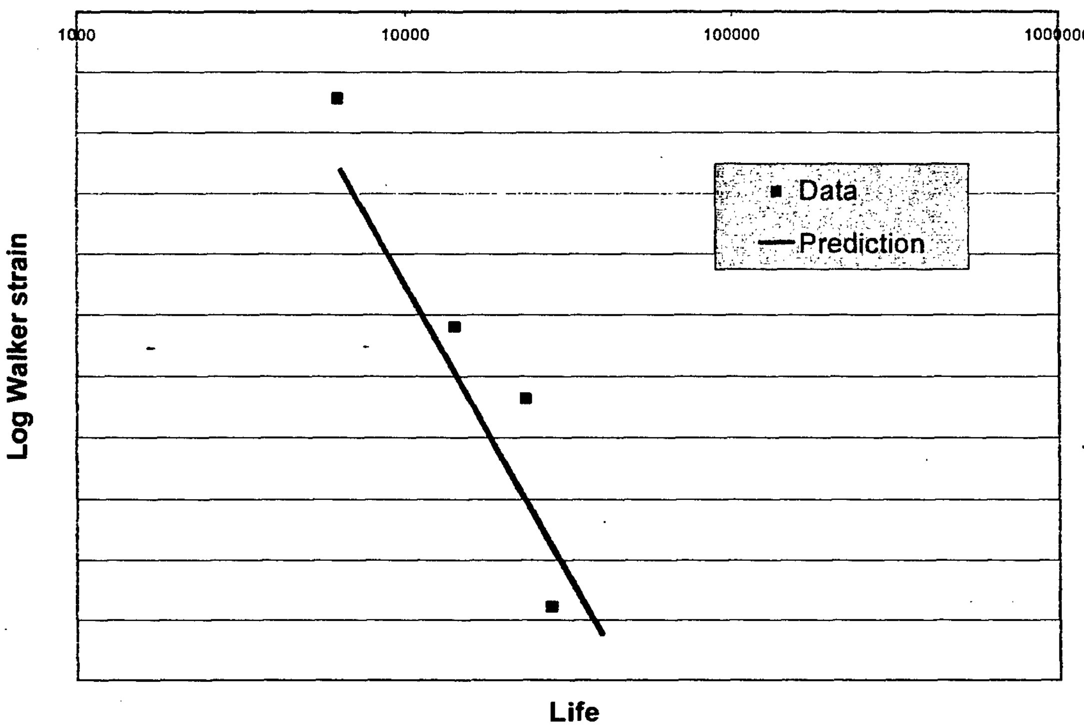

Figure 7: Kt 2.29 400C, data against prediction

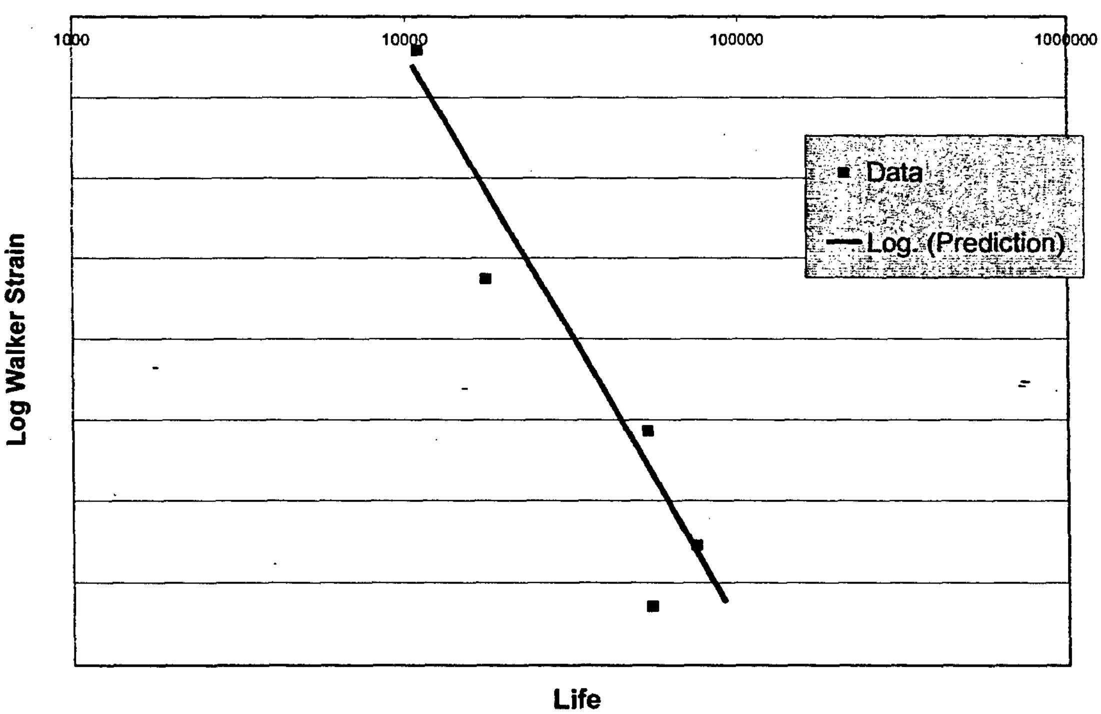

Figure 8: Kt2.29 500C, data against prediction

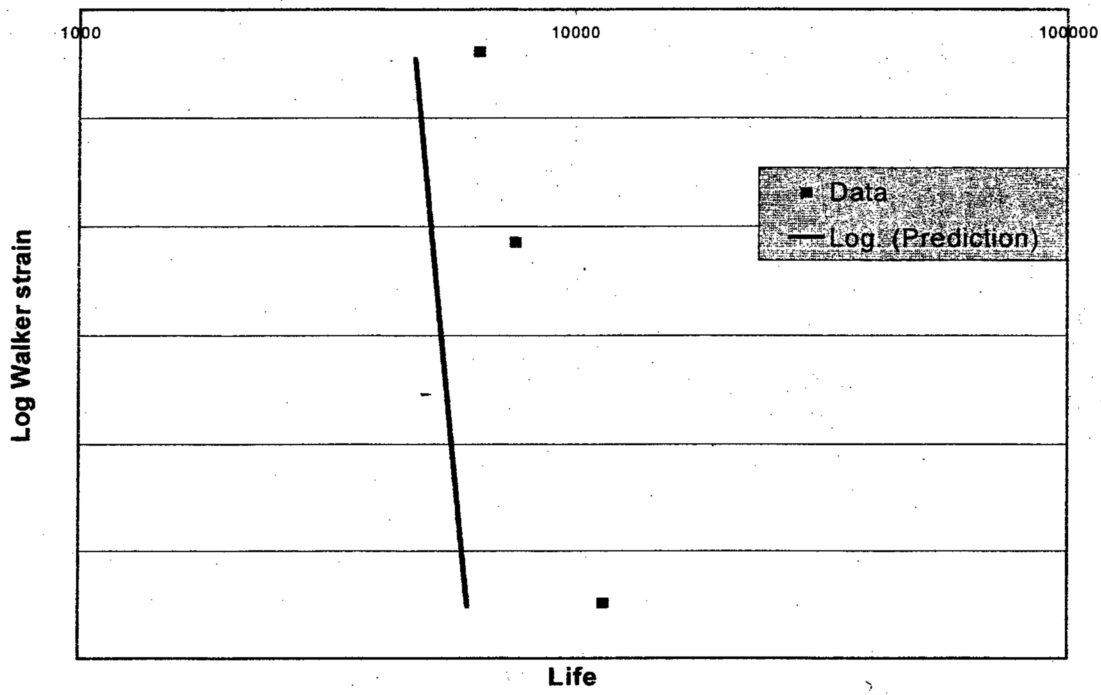

Figure 9: Kt 2.29 600C, data against prediction

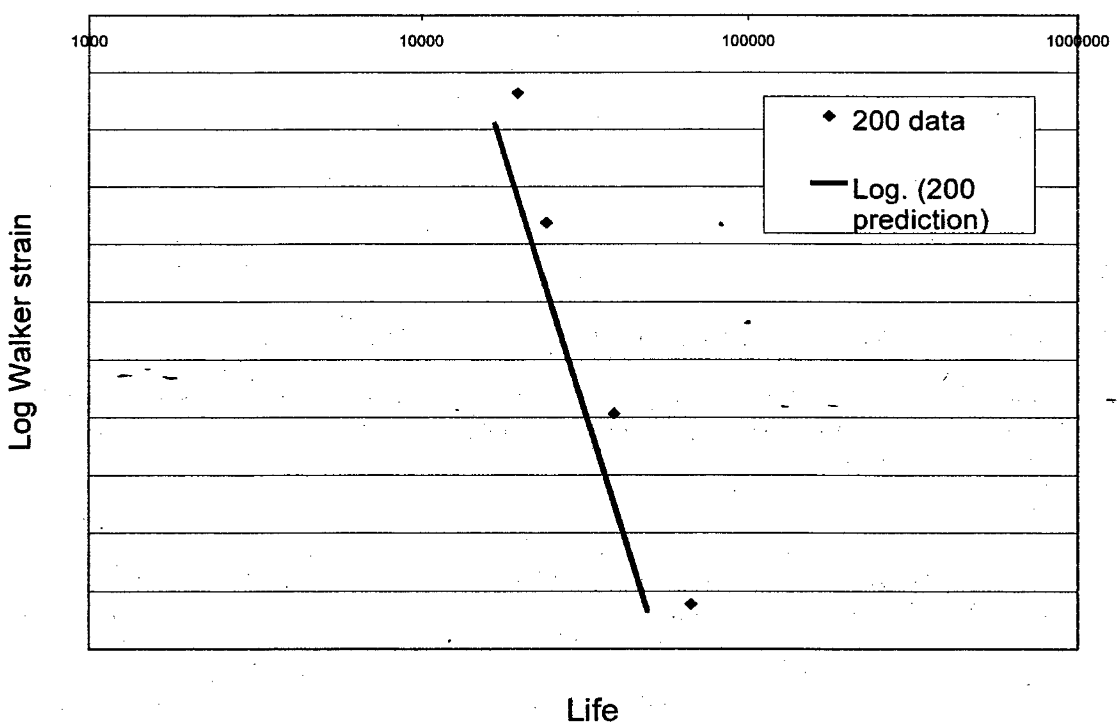

Figure 10: Kt 1.66 200C data with revised prediction

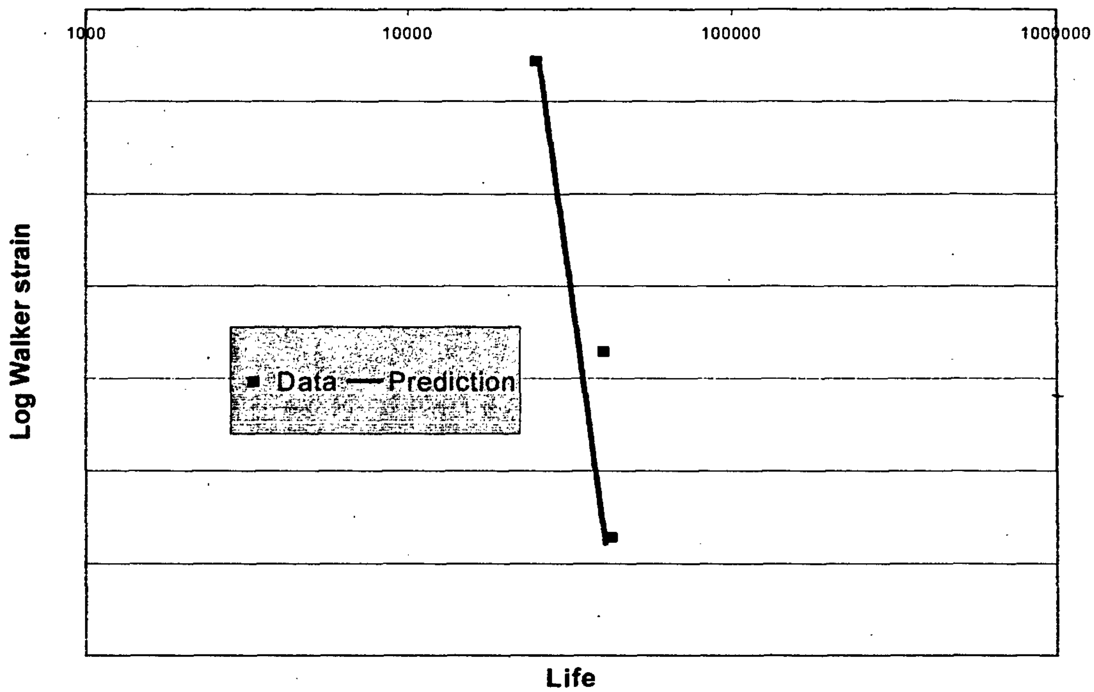

Figure 11: Component bore test data against prediction

Paper 23: Discussion

Question from Dr R Szczepanik – Instytut Techniczny Wojsk Lotniczych, Poland

Could we, in Poland, use this risk-regulated inspection methodology for engines of Soviet-origin, bearing in mind that they have a wide distribution of material properties relative to comparable western materials?

Presenter's Reply

It should be possible to apply risk-regulated inspection to the Polish fleet case. Assuming that the situation is that budgets are very small but labour is relatively inexpensive, then frequent disassembly and inspection might be the most effective option, depending on the effort required in removing and re-fitting the engines. One may be able to take account of the fact that the fleets may have already consumed significant life, as the basis for calculation of a safe inspection interval. That is, if many components have survived to a certain life, then this should say something about the crack propagation life capability of the components. However, a disadvantage of frequent inspections is that they increase the risk of handling damage and build errors.